TRAY SEDIMENTATION
WITH
SYPHON CONTROLS

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ROBERT J. KOWAL

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Abstract

This thesis presents the theory of sedimentation necessary for the design of a secondary clarifier, for applications where complete solids recycle is practiced. The development of tray clarification is briefly examined by looking at some of the problems encountered in past attempts of design. A design guideline is presented for a clarifier which utilized trayed levels to aid in sedimentation, and overcomes sludge removal problems of the past attempts at tray sedimentation, by using syphons to control flow. Solids are removed by flushing them from the trays. The design presented takes advantage of shallow settling depth, reduced overflow rate, reduced effect from outlet currents, and minimizes the effect of short-circuiting; and additionally, offers a means whereby future expansion may be made quite simply by rescheduling the operation.

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Tray Sedimentation

with

Syphon Controls

1. INTRODUCTION

In 1974, the city of Brandon, Manitoba, completed a project to alleviate their problem of insufficient winter storage in their sewage lagoons. The project involved the construction of an extended aeration treatment plant for winter operation. The secondary treatment thus provided allows the city to continually discharge the treated effluent to the Assiniboine River via the existing lagoons.

A novel design in the treatment plant is the secondary clarifier where clarification occurs in sedimentation channels that have three trayed levels. The idea of utilizing trays to aid in the sedimentation process is not new, although, earlier attempts by others were not very successful as practical problems were encountered with sludge removal (1,2)*.

1.1. Purpose and Scope

The original purpose of this paper was to evaluate the clarification system at Brandon, Manitoba. Due to operational problems within the treatment plant, the system did not provide a degree of treatment suitable for

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* The numbers in parenthesis indicate references used in the text.

evaluation. The project was not abandoned since the novel design of the clarifier deserves further investigation. Some data of suspended solids concentrations are included as appendix B, although the reader should keep in mind that the results are not representative of the clarifier because an aerobic sludge floc did not develop.

The purpose of this paper is to present the design of tray sedimentation of wastewaters. Tray sedimentation with syphon controls utilizes a system of syphons to allow for a removal of collected solids from the clarification process and to control effluent draw-off. This paper attempts to compile the information on the design and to indicate important aspects of it. The design is directed mainly towards an application where complete recycle of settled solids is required.

2. SEDIMENTATION

Sedimentation is the removal of solid particles from suspension through gravity settling. The terms settling, sedimentation, clarification or thickening all refer to the removal of settleable solids, although clarification implies an interest in the quality of the clarified liquid; whereas, thickening implies an interest in the concentrated solids being collected (3).

The term tray sedimentation is derived from the fact that trays are incorporated to aid in the collection of settleable solids. In tray sedimentation the basic fundamentals of settling are much more clearly evident than in the more conventional settling tank design used today. Hence, a review of the fundamental process of sedimentation is provided to allow the reader a better understanding of this paper.

2.1. Classification of Sedimentation

Sedimentation is a unit operation of sanitary engineering. In wastewater treatment, the unit operation of settling is used to remove: grit, organic particulate-matter in the primary settling basin, biological floc in the activated sludge settling basin, chemical floc from chemical coagulation and for solids concentration in sludge thickeners (4).

The settling of particles has been classified into four separate categories: type I - discrete, type II - flocculent, zone and compression settling (3,4,5). The classification for the type of settling is dependent on the concentration of the suspension and the character of the solids. It is common to have more than one category of settling taking place in one clarifier. In the sedimentation of raw domestic sewage, all four may be occuring simultaneously.

Type I settling refers to the sedimentation of discrete, nonflocculating particles in a dilute suspension (4). The solids settle with no interaction between neighbouring particles, e.g. a solution containing grains of sand.

Type II settling refers to a dilute suspension of particles that flocculate or coalesce during sedimentation (4). Through flocculation or coalescing, the particles increase in mass and settle at a faster rate.

Zone settling refers to concentrated suspensions where interparticle forces are sufficient to cause a hindering of the settling. The particles settle in fixed positions with respect to each other and settle as a unit or zone (4).

Compression settling refers to the conditions which develop when the particles settling are of such concentration that a structure is formed. Further settling can only occur through compression of the structure (4). The compression is due to the weight of the particles being added on the top of the structure.

2.2. Type I - Discrete Settling

The settling of discrete, nonflocculating particles in a dilute suspension settle unhindered by the presence of other settling particles and is a function only of the properties of the fluid and particles in question (3).

The settling of a discrete particle can be described through the classical laws of mechanics. A list of the forces acting on a particle moving through a fluid are: the force due to gravity, the buoyant force due to the fluid, and the frictional or drag force. The resultant

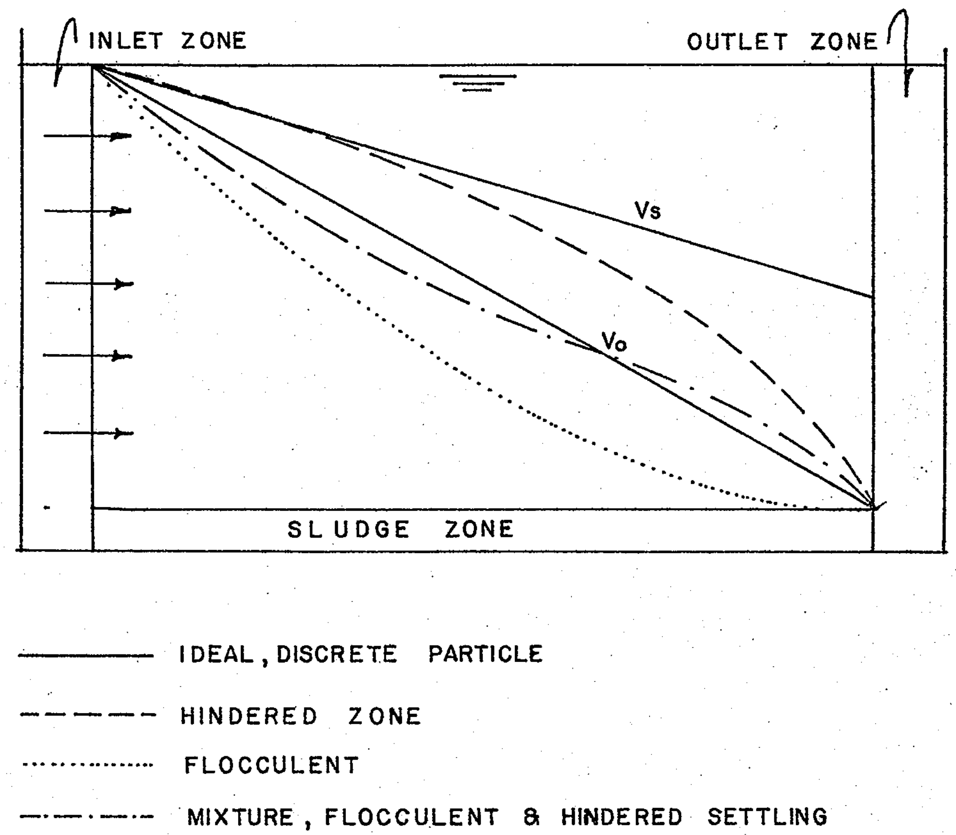


Figure 1: Discrete particle settling.

(Weber, J.W. Jr., Physicochemical Processes for Water Quality Control, Wiley-Interscience, New York, N.Y., 1972. p. 116) force acting on any particle is then:

$$F_R = F_W - F_B - F_D \qquad \text{.............} \; (1)$$

where F_R = resultant force, lb. (force)
F_W = force due to gravity, lb. (force)
F_B = buoyant force, lb. (force)
F_D = drag force, lb. (force)

The gravitational force may be calculated by (6):

$$F_W = \rho_s \, V_p \, g \qquad \text{.............} \; (2)$$

where ρ_s = particle density, lb. (mass) per cu. ft.
V_p = particle volume, cu. ft.
g = acceleration due to gravity, 32.17 ft. per sec.^{2}

The buoyant force may be calculated by (6):

$$F_B = \rho_l \, V_p \, g \qquad \text{.............} \; (3)$$

where ρ_l = fluid density, lb. (mass) per cu. ft.

The drag force, a function of the size, roughness, shape and velocity of the particle and of the fluid density and viscosity have been found experimentally to be related as (3):

$$F_D = \frac{C_D \, A_p \, \rho_l \, v_s^2}{2} \qquad \text{..............} (4)$$

where C_D = Newton's dimensionless drag coefficient

A_p = projected surface area of the particle in the direction of flow, sq. ft.

v_s = the relative velocity between the particle and the fluid, ft. per sec.

The drag coefficient, C_D, has been experimentally demonstrated to be related to the Reynold's number, Re (3). The Reynold's number is a ratio of the inertia force per unit area to the viscous force per unit area (7). A relationship, considering spheres for particles, is that for Reynold's numbers between 1 and 10^4, C_D can be approximated by (8),

$$C_D = \frac{24}{Re} + \frac{3}{\sqrt{Re}} + 0.34 \qquad \text{........ (5)}$$

Particles other than spheres tend to have increased drag coefficients due to changes of shape (9).

Discrete particles settling under the influence of gravity continue to accelerate until the drag force is equal to the gravitational force. Considering a spherical particle:

$$\frac{3}{4} \; \frac{C_D \, \rho_1 \, v_s^2}{\rho_s \, D_p} = g \, \frac{\rho_s - \rho_1}{\rho_s} \qquad \text{........ (6)}$$

where D_p = particle diameter, ft.

When the acceleration of the particle becomes zero the settling velocity is constant. This velocity value is known as the terminal velocity u_t (3):

$$u_t = \left[\frac{4}{3} \frac{g}{C_D} \left(\frac{\rho_s - \rho_l}{\rho_l} \right) D_p \right]^{\frac{1}{2}} \qquad \ldots\ldots. (7)$$

where u_t = terminal settling velocity, ft. per sec.

Under normal conditions, generally the terminal velocity is quickly attained (3). If the terminal velocity of a suspension of discrete particles of uniform size and shape is known, the clarification rate can be easily computed (3):

$$q = \frac{Z}{t} A = u_t A \qquad \ldots\ldots. (8)$$

where q = volumetric rate of clarification, cu.ft./sec.
Z = distance through which particles settle in time t, ft.
t = time, sec.
A = cross-sectional area of a volume in a plane perpendicular to the direction of subsisdence, sq. ft.

With reference to equation 8, all particles with a terminal velocity equal to or greater than u_t will be removed.

In sedimentation of discrete particles, the flow

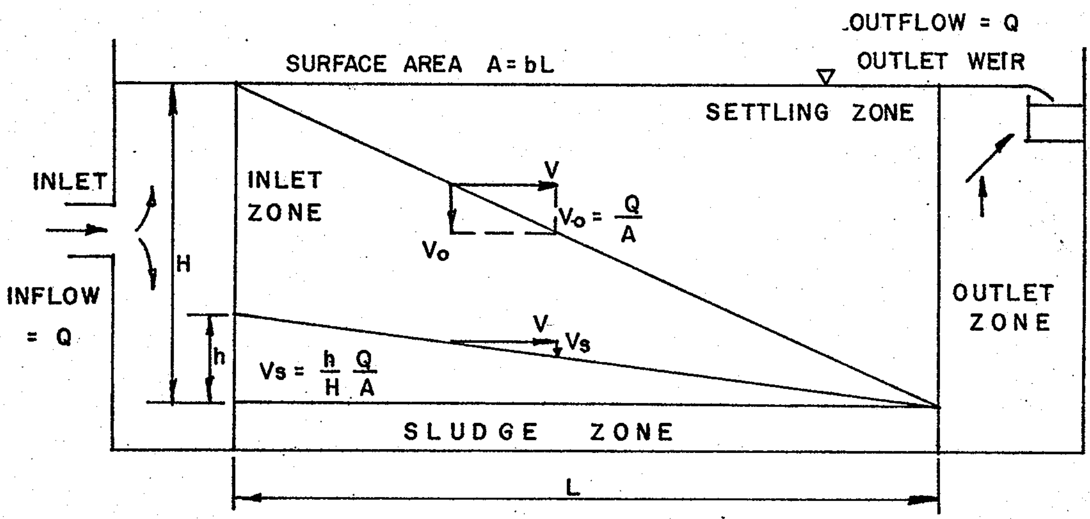


Figure 2: Sketch of an ideal rectangular sedimentation basin, indicating the settling of discrete particles.

(Clark, J.W., Viessman, W. Jr., Hammer, M.J., Water Supply and Pollution Control, second edition, International Textbook Co., Scranton, Ontario, 1971. p. 329) capacity of the basin is theoretically independent of the basin depth and is a function only of the surface area for the basin and the settling velocity of the particle (3).

Discrete particles can be seen to settle at a constant velocity. The proportion of particles entering a settling tank that will be removed can be calculated from figure 2.

The depth of the tank is the product of the settling velocity and the retention time, t_o (5).

$$\frac{h}{H} = \frac{v_s t_o}{v_o t_o} = \frac{v_s}{v_o} \qquad \text{..........} \; (9)$$

Hence, the proportion of particles of a given size that will be removed in a horizontal flow tank are (5):

$$\frac{v_s}{v_o} = \frac{v_s}{Q/A} \qquad \text{.........} \; (10)$$

where Q = rate of flow

A = surface area of the settling zone, width x length

v_s = settling velocity of the particle

v_o = settling velocity for 100% removal

Suppose the rectangular horizontal basin being discussed is altered to have an intermediate tray placed at the half-way depth. The velocity of the water in the tank has not been changed and the settling velocity of

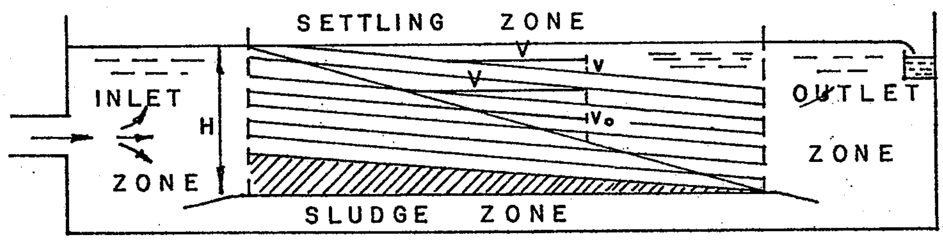


Figure 3: Zones of a rectangular, horizontal, continuous-flow sedimentation basin.

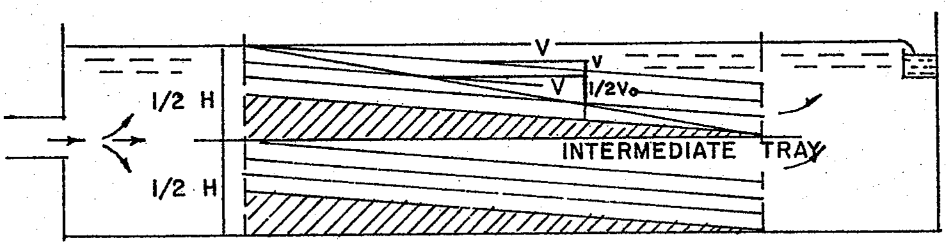


Figure 4: Tray in tank provides added floor area and increases solids removal.

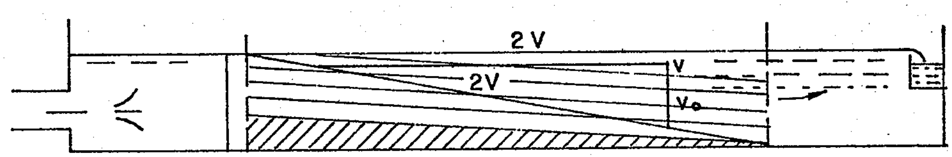


Figure 5: Reduced tank depth does not increase removal ratio.

(Camp, T.R., "Studies of Sedimentation Basin Design" Sewage Works Vol. 25, January 1953. Pp. 2,3.)

the particles remains the same. The depth through which the particles must settle is reduced by one-half and there is twice the floor area available to collect solids. The removal ratio has been doubled by the addition of the additional floor area (1).

If the idealized basin is constructed to only the half-way depth, the velocity of flow through the tank will be doubled, and all particles settling in this tank will have one-half the slope of corresponding paths for particles settling in the original settling basin. The removal ratio for the tank with twice the velocity and only half the depth is exactly the same as the original tank with the unaltered depth and velocity. It can be seen that the change in depth does not affect the removal ratio. Only changes in the surface or floor area and the settling velocity affect the removal ratio.

2.3. Type II - Flocculent Settling

The settling of particles, which are not discrete but will coalesce or flocculate during settling, have varying settling rates due to the increase in mass of the solids from flocculation. The degree of flocculation occuring is dependent on the overflow rate, the depth of the basin, the velocity gradients in the system, the concentration of particles, and the range of particle sizes (4). The overflow rate is "the unit volume of flow per unit of time divided by the unit tank area" (10). In effect it is the average upflow velocity of the fluid through the settling solids.

The determination of the settling characteristics for a suspension of flocculent particles can only be obtained through a settling column analysis. The column may be of any reasonable diameter but the depth should be equal to or greater than the depth of the proposed design. A settling column analysis is conducted by allowing the suspension to settle under quiescent conditions. Samples are withdrawn at different time intervals at various depths and the concentration of particles is determined for each sample. The percent removals, of particles based on the original concentration, are calculated and plotted on a grid of depth versus time of settling. Isoconcentration lines connecting points of equal percent removal are drawn. These lines represent a "depth-time ratio equal to the minimum average settling velocity of the fraction of particles indicated" (3). The curvature of the lines represents the flocculating nature of the particles. Non-flocculating particles would plot as linear lines (3).

In conducting a settling column analysis, care must be exercised to ensure the original suspension is representative of the actual suspension being designed for, that a homogeneous mixture exists at the start of the test, and that the temperature of the suspension and the surrounding air are approximately equal (3,4). Temperature

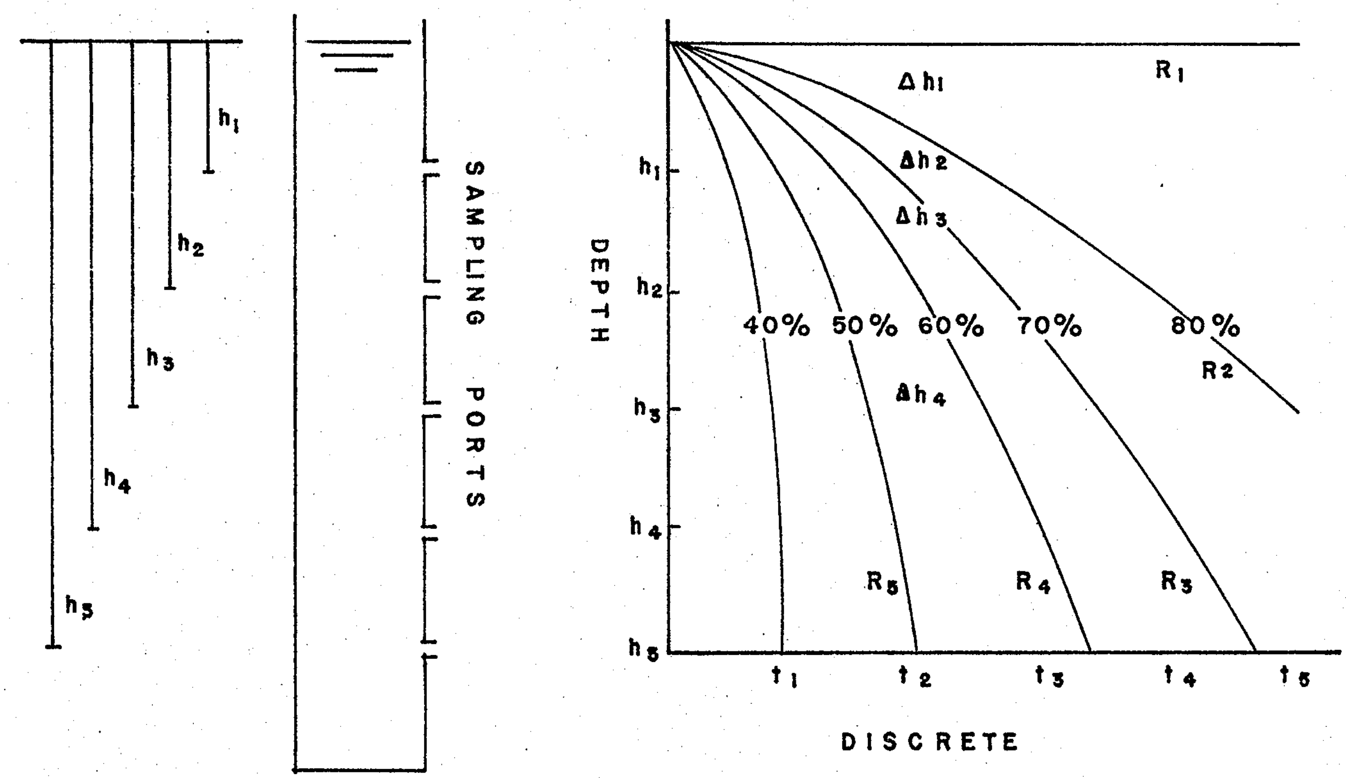


Figure 6: Quiescent settling column and settling curves for flocculent particles.

(Adapted from Metcalf and Eddy Inc., Wastewater Engineering: collection, treatment, disposal, McGraw-Hill Book Co., New York, N.Y., 1972. p. 289) variations will develop convection currents which disrupt settling.

In figure 6, the percent removal of solids at time, t_2, for a basin of depth, h_5, at a clarification rate, q_o, is determined from the plotted grid.

$$q_o = \frac{h_5 A}{t_2} = u_{t_o} A \quad \ldots\ldots\ (11)$$

where $\frac{h_5}{t_2}$ = the average settling velocity of the particles during time, t_2.

The overall percent removal, considering particles with settling velocities greater than $\frac{h_5}{t_2}$ can be calculated by (3):

$$\text{Overall Percent Removal} = \frac{\Delta h_1}{h_5}\left(\frac{R_1 x R_2}{2}\right) + \frac{\Delta h_2}{h_5}\left(\frac{R_2 x R_3}{2}\right) + \frac{\Delta h_3}{h_5}\left(\frac{R_3 x R_4}{2}\right) + \frac{\Delta h_4}{h_5}\left(\frac{R_4 x R_5}{2}\right) \quad \ldots\ldots\ldots\ldots\ (12)$$

Metcalf and Eddy suggest that to achieve the desired removals indicated by settling tests, design settling velocities or overflow rate should be multiplied by a factor of 0.65 and that the detention times should be multiplied by a factor of 1.75 or 2.0 (4).

In clarification of particles which are of a flocculent nature, the removal ratio is dependent on depth as well as the properties of the fluid and the particles.

2.4. Zone Settling

Zone settling occurs in solutions of concentrated suspensions where during settling the particles aggregate, forming a mass. The settling of the mass of particles is obstructed by the flow of upward displaced fluid and hindered settling occurs. The mass of particles settle as a blanket maintaining the same relative positions with respect to each other (4).

Distinct zones appear as the settling process proceeds. At the uppermost surface a clarified zone of clear water develops. Gradually, the clarified zone increases in depth and an individual particle settling zone develops beneath. The individual settling extends until the particles become hindered by the mass of solids below. A division, characterized by a water-solids interface, separates the individual particle settling zone from the hindered zone. The division appears as a "blanket" of solids. In the hindered zone, the particles settle at a reduced rate and no individual particle movement is observed (3). Eventually, the lower solids of the hindered zone begin to collect and collide with other particles already settled on the bottom of the basin. These colliding particles cause particles above to suffer a reduction in their downward settling velocity. This area of changing

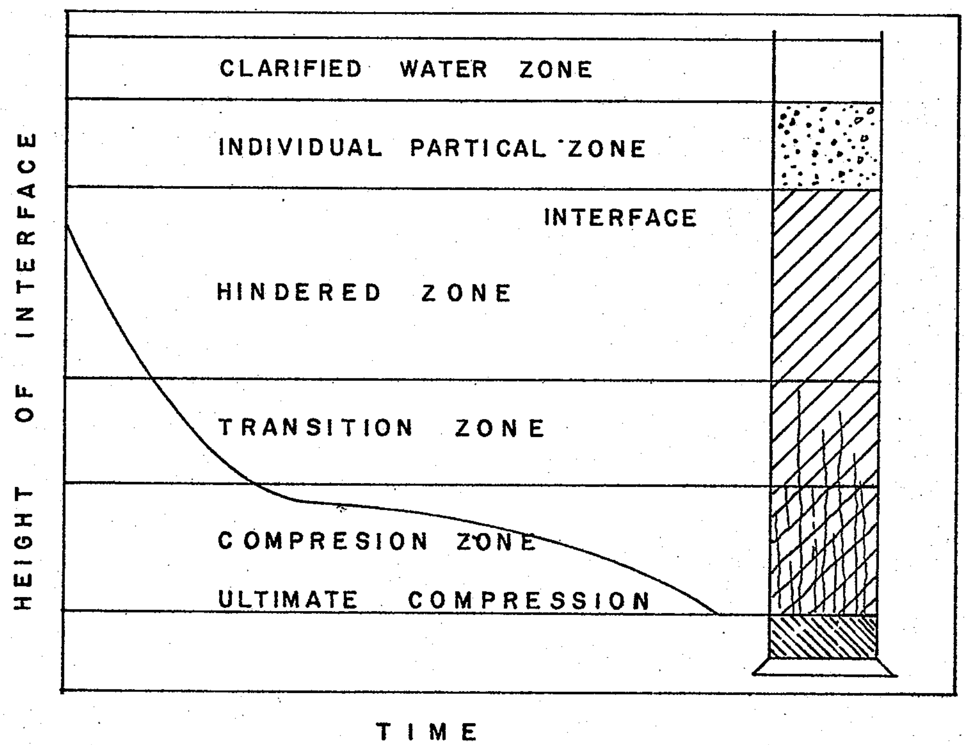


Figure 7: Settling zones.

(Eckenfelder, W.W. Jr., <u>Water Quality for Practicing Engineers</u>, Barnes and Noble, Inc., New York, N.Y., 1970. p. 118) settling velocity is referred to as a transition zone. The collected particles on the bottom of the basin represent an area where compaction or compression of the solids is continuing. The solids structure is compacted due to the increasing weight of solids collecting above and is referred to as a compression zone (4).

The overflow rate determination for zone settling particles should be based on three factors, as outlined by Metcalf and Eddy: 1) the area needed for free settling in the discrete settling region; 2) the area needed on the basis of the rate of settling of the interface between the discrete settling region and the zone settling region and 3) the rate of sludge withdrawal from the compression region. Generally, the rate of zone settling is usually less than the rate for free settling. Hence, the free settling rate is rarely the controlling factor (4).

The area required to separate concentrated suspensions is dependent on the clarification and thickening capacities. The clarification capacity can be taken from the initial rate at which the solids-liquid interface subsides (see figure 7) and is related to the settling velocity of the sludge. The settling velocity of the sludge interface must be greater than the vertical rise velocity of the liquid (3,11). The thickening capacity can be calculated from an analysis of the behaviour of a suspension undergoing batch sedimentation. Thickening capacity is related to the depth of sludge in the basin and the time the sludge is in the compression zone (3,11).

The critical area for thickening is given by (4):

$$A = \frac{Qt_u}{H_o} \qquad \text{.............} \quad (13)$$

where A = area required for sludge thickening, sq.ft.
Q = flowrate into tank, cu.ft./sec.
H_o = initial height of interface in column, ft.
t_u = time to reach desired underflow concentration, sec.

The critical concentration controlling the sludge handling capability of the tank is at height H_2, when the concentration is C_2.

A means of graphically determining the critical concentration and time for desired underflow concentration is (4):

a) Critical concentration, C_2

1) Extend tangents from the free settling and compression regions of the curve until intersection, 2) bisect the angle formed, and 3) project the bisector to the curve. The point on the curve indicated by the bisector is the critical concentration, C_2.

b) Settling time, t_u

1) A horizontal line corresponding to the height of the solids at the desired underflow concentration, C_u, is drawn at height, H_u.

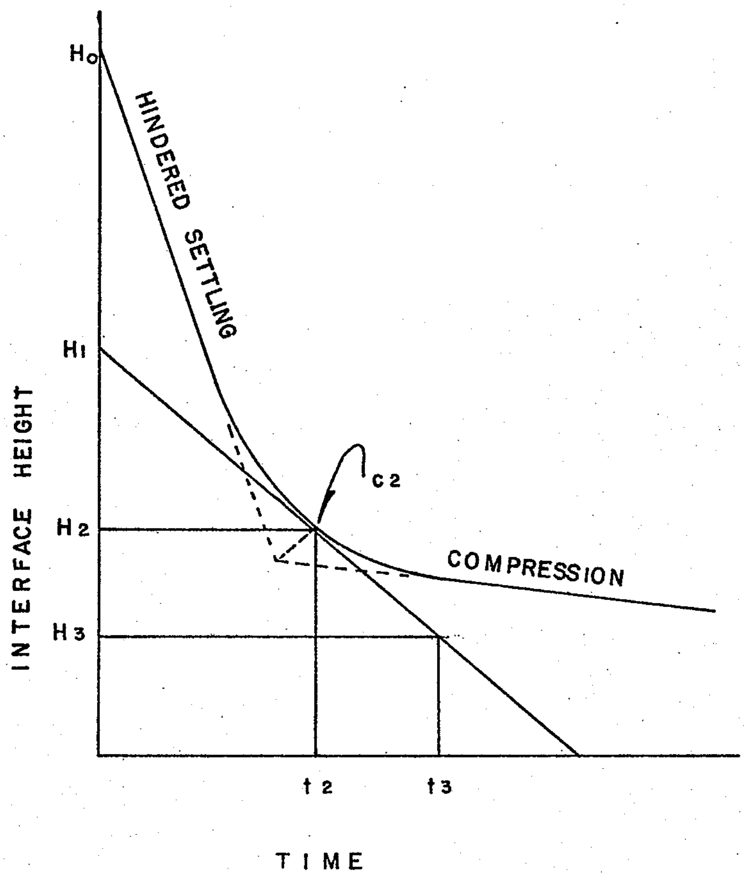


Figure 8: Graphical analysis of interface settling curve.

(Metcalf and Eddy Inc., Wastewater Engineering: collection, treatment, disposal, McGraw-Hill Book Co., New York, N.Y., 1972. p. 292)

$$H_u = \frac{C_o H_o}{C_u} \qquad \text{.......... (14)}$$

2) At the critical concentration, C_2, a tangent is constructed and 3) where the tangent and the horizontal line at height, H_u, intersect, a vertical line is drawn to the time axis determining t_u, The value of t_u is the time required to reach the desired underflow concentration.

2.5. Compression Settling

Compression is the consolidation of particles in the zone of compression. The consolidation of the layers of particles is a slow process with the rate of consolidation being approximated as (3):

$$-\frac{dZ}{dt} = K(Z-Z_\infty) \qquad \text{.......... (15)}$$

where Z = height of sludge line, ft.
Z_∞ = final height of sludge line, ft.
K = constant for a given suspension, sec.^{-1}

Compaction is generally aided by gentle stirring. This tends to break up the floc permitting water to escape (4).

2.6. Scour Velocity

In horizontal flow clarifiers, forces on settled particles are caused by the force of the water flowing over them. In settling basins, the horizontal velocity should be kept low so that settled particles are not scoured from the bottom of the basin. An equation developed by Camp for the critical velocity is (9):

$$V_H = \left[\frac{8k(s-1)gd}{f}\right]^{\frac{1}{2}} \qquad \text{..........} \quad (16)$$

where V_H = horizontal velocity that will just produce scour, ft. per sec.

s = specific gravity of particles, lb. per cu. ft.

d = diameter of particles, ft.

k = constant which depends on type of material being scoured

f = Darcy-Weisbach friction factor

Typical values of k are 0.04 for unigranular sand and 0.06 or more for sticky interlocking matter with typical values of f being 0.02 to 0.03 (4).

2.7. Application of Sedimentation Theory

The application of sedimentation theory to actual design may seem a bit obscure. The majority of the theory presented is in a simplified form with settling occuring under ideal conditions. This was done to uncomplicate the problem and allow for a better explanation of the process being considered. A better look at the operation of a continuous flow basin aids in applying the theory.

A continuous horizontal flow sedimentation basin of rectangular design may be divided into four distinct zones, as illustrated in figure 3.

The inlet zone is assumed to disperse the incoming fluid uniformly over the entire cross-section of the tank. The flow should be dispersed such that the motion of the fluid is in a horizontal direction for the entire cross-section and travels horizontally through the settling zone. In the settling zone, the suspended particles settle as if they were settling in a tranquil water with the exception of the horizontal motion. The settled solids are collected below the settling zone in a sludge zone. The sludge zone is provided to ensure that the collected solids do not reduce the size of the settling zone and is designed large enough to ensure that the settling solids are not disturbed by mechanical sludge removal equipment. The outlet zone, where the clarified effluent is collected and discharged, is regulated by an outlet weir (5).

The relationship of continuous flow operation to batch sedimentation, using theory developed for an ideal basin, would be to assume a rectangular basin of depth equal to that of a settling column analysis. The sedimentation process observed in the column would be the same in the basin, except that the settling would occur along the length of the tank, as if the column were moving horizontally. The sediment would settle at the bottom, collecting along the horizontal length instead of in a mass under

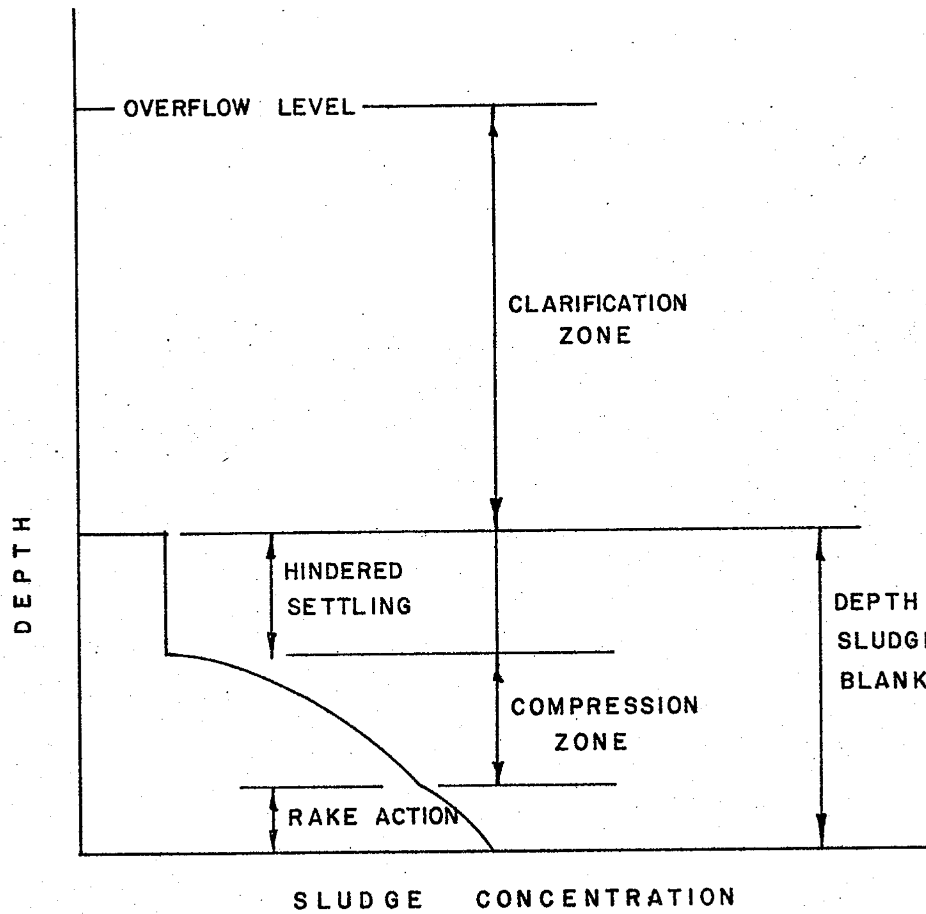


Figure 9: Sedimentation in a secondary settling tank.

(Eckenfelder, W.W. Jr., Melbinger, N., "Settling and Compaction Characteristics of Biological Sludges 1. General Considerations", Sewage and Industrial Wastes, Vol. 29, 10, 1114. p. 115) the column height. This similar pattern of sedimentation may be observed in a circular horizontal flow basin moving from the center well to the outer wall (3).

A schematic representation of the activity taking place in a secondary clarifier enhanced by the hydraulic movement of sludge collection rakes is illustrated in figure 9. Note the zones required for settling and the appropriate depth of each zone.

In the proper design of a final clarifier three criteria must be satisfied, as outlined by Clark, Viessman and Hammer: "a) the clarification capacity required by the hindered settling rate, b) thickening capacity needed to remove material in the transition and sludge zones (compression zone), and c) the detention period cannot be excessive, otherwise the bottom may become anaerobic" (6).

2.8. Short-circuiting

The efficiency of settling basins is reduced by currents (3,4,5,6). Currents can be created by a) the inertia of incoming fluid, b) wind action, c) thermal induction, and d) introduction of fluid of a different temperature than the fluid of the basin. These currents are referred to as eddy, surface, vertical convection, and density currents, respectively (8).

The effect of currents on a settling basin, causing reduced efficiency for solids removal, is called short-circuiting. Short-circuiting is the interruption of the flow pattern due to extraneous currents, or as defined by Clark, Viessman and Hammer is "the deviation from plug flow which is exhibited by fluid particles passing through a reaction vessel" (5). Plug flow under ideal conditions occurs when fluid particles entering a basin, flow the length of the tank in the designed detention time, $t_o = V/Q$. If short-circuiting occurs, the flow through time will be some time less than t_o and the flow will not utilize the entire volume of the tank.

The degree of short-circuiting can be determined by using tracer studies on a model of the settling basin. Some tracers which may be used are dyes, electrolytes, radioactive isotopes or other suitable material which does not settle or stratify (12). The tracer solution is introduced as a slug through the inlet and the concentration is measured at the outlet as a function of time. The results of a basin test are plotted as dimensionless figures with the vertical axis being the relative concentration of the tracer, C/C_o, and the horizontal axis being the relative time ratio t/T. The term C = the concentration of tracer at outlet time, t; C_o = the weight of tracer divided by the tank volume; t = the time; and T = the theoretical detention time (volume of tank divided by flow rate) (13).

An evaluation of a plot for tracer concentration versus time of flow, a flow curve, can reflect the degree of dead spaces in a basin and allow for a calculation of the variances and flow tendencies. Figure 10 represents

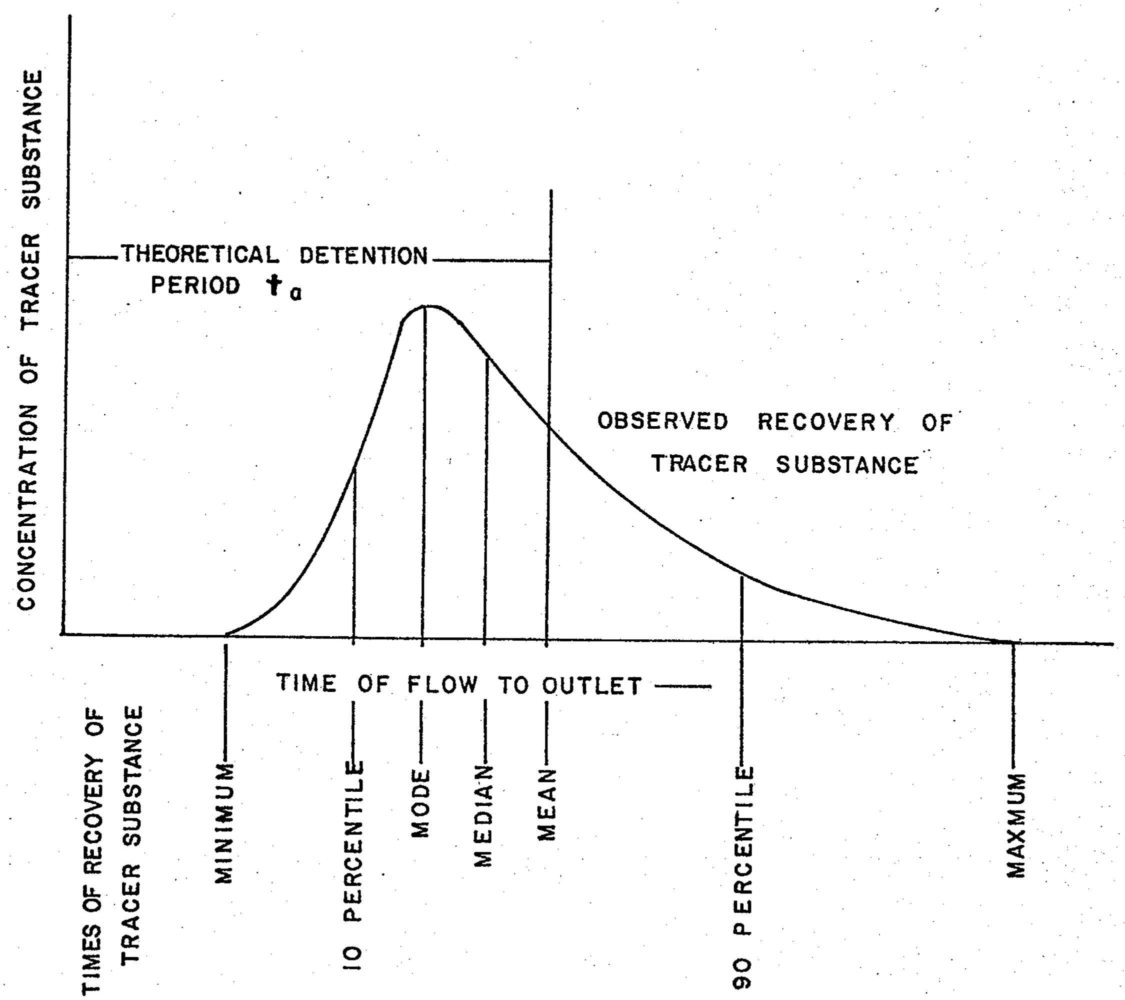


Figure 10: Dead spaces and short-circuiting in a settling basin are reflected in the concentration and time of recovery of tracer substances.

(Fair, G.M., Geyer, J.C., Okun, D.A., Water and Wastewater Engineering Vol. 2 Water Purification and Wastewater Treatment and Disposal, John Wiley and Sons Inc., New York, N.Y., 1968. p. 25 - 15) a typical curve and illustrates the information which can be collected.

The mode time corresponds to a maximum tracer concentration, C/C_o. The median is the time at which one-half of the area is confined by the flow curve, t_h/T, where t_h = median time. In a basin with no dead spaces, the average detention time would correspond to the theoretical detention time, $t_a/T = 1$, where t_a = mean detention time. Dead spaces are characterized by values of t_a/T being less than 1. If a tracer diffuses into dead spaces early in the test and slowly diffuse out later, the curve will have a characteristic "long tail". This elongation of the curve would create misleadingly high values of t_a/T. High values of t_M/T indicate good hydraulic efficiency, where t_M = mode time. Additional information may be obtained through a calculation of the 10 and 90 percentiles. A ratio of the percentiles called the dispersion index or Merril index, t_{90}/t_{10}, indicates the degree of mixing in the basin. The larger the value, the more mixing has occurred. The reciprocal of the dispersion index is the volumetric efficiency. Very low values indicate that the total volume of the basin is not being utilized. If after repeated tests, the time-concentration curve cannot be reasonably reproduced, the flow through the basin is considered unstable (8,13).

Typical dispersion curves for tanks are illustrated in figure 11. Curve A represents the theoretical

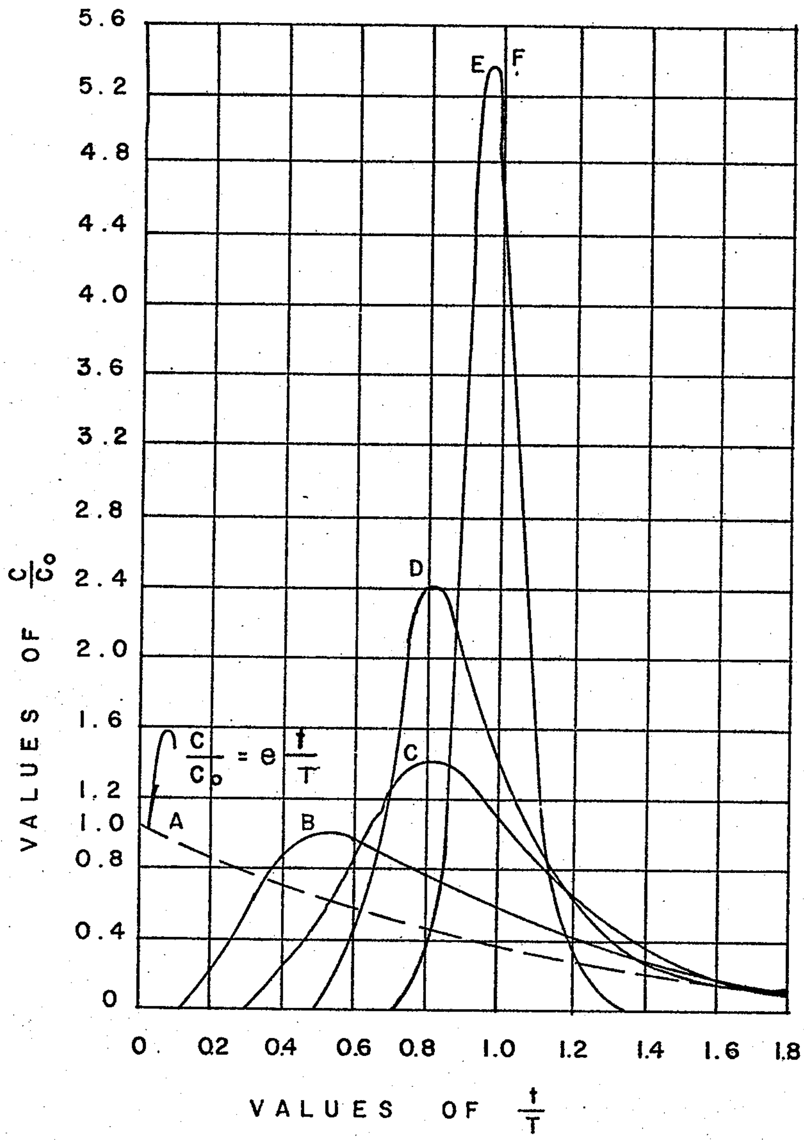


Figure 11: Typical dispersion curves for tanks.

(Camp, T.R., "Studies of Sedimentation Basin Design", <u>Sewage Works</u>, Vol. 25, 1, 1. p. 7) curve for an ideal dispersion in which the tracer slug is mixed instantaneously with the tank contents. Some degree of short-circuiting is associated with curve A due to the appearance of tracer very quickly at the outlet end. Curve B is characteristic of a radial flow circular tank under unstable conditions. Curve C is characteristic of a wide rectangular basin with a relatively shallow depth and curve D is characteristic of a long narrow rectangular tank. Curve E is characteristic of a round-the-end baffled mixing chamber, very long as compared to width and depth. Curve F is representative of an idealized tank as illustrated in figure 3 (2).

3. PREVIOUS EXPERIENCE OF TRAY SEDIMENTATION

Tray sedimentation, as presented by Camp (9), was used in the chemical and metallurgical industries prior to its proposed use in sanitary engineering (14). The only difference in the two applications was in the nature of the solids being removed.

An early attempt at the application of tray settling was made in 1915. A series of conical, circular trays were placed one above the other to form several shallow settling compartments. The solids collected on each tray and were scraped into a centrally located collection tube. The tube carried the solids to the bottom of the tank where they were removed (15).

In 1940, at Springfield, Missouri, an application of a rectangular basin with trays was attempted. Problems developed due to the anaerobic digestion of solids which were not adequately removed. Rising gas caused some sludge to float as scum, which further digested. The gases produced could not escape due to the presence of the superimposed trays and finally caused the trays to lift and break (14).

Another application was at the Cambridge, Massachusetts water treatment plant where a 16 foot deep basin was modified by the addition of two intermediate trays. The incoming pre-flocculated water was to have three passes, due to the intermediate levels, where sedimentation could occur. The additional floor area provided for three times the previous solids removal capacity and reduced the liquid overflow rate. The rate of alum floc build-up was quite low resulting in the trays only requiring cleaning about every ten days. Settled solids were removed from the trays by draining the entire basin and washing each level (1).

In 1953, Camp, re-emphasized the advantages which could be achieved if tray clarification was developed. He further stated that....

> "It is not now practicable to use such a settling basin, because no satisfactory sludge removal equipment has yet been developed for basins of this type." (2)

Camp did suggest that in water treatment plants which did not require a large amount of sludge collection, tray clarification could be utilized. Cleaning could be done by taking the basin out of service and dewatering it, with the collected solids being flushed to drains with hand hose or by monitor nozzles. (2)

Another design of a circular sedimentation basin with trays superimposed one above the other around the outer wall was tried. Sludge removal was mechanical, with a revolving arm scraping the sludge to a central point.

> "Apparently the combination of cost and performance has not justified the adoption of such a devise in practice." (16)

The early applications of tray sedimentation were all limited by sludge clearing or removal problems. The basins were either rendered useless or were required to be taken out of service to be cleaned. The practicality and/or expense of any reasonable design, placed limits on the further development of tray sedimentation.

4. ADVANTAGES OF TRAY CLARIFICATION

The advantages offered by the use of tray clarification, applied to the extended aeration process, can be readily seen from the theoretical concepts of sedimentation. Rectangular trayed settling basins do not have to provide additional length required to remove the slower settling particles and the slower settling particles are more readily removed in trays because of the shallower settling depth.

The necessary detention time of 1 - 4 hours required for the conventional process of settling can be reduced to a few minutes based on the theoretical concepts of settling. The reduced depth, because of the trays, provides for quicker settling of the sludge.

The superimposing of trays one above the other provides a much greater floor area for the collection of solids causing a reduction of the overflow rate of the basin. The more practical means of designing a settling basin for the removal of flocculent solids is by considering the overflow rate.

The problems of sludge removal from the early designs of tray clarifiers and the lack of an adequate attempt to develop a means of effectively removing collected sludge resulted in the abandonment of the tray-settler concept. However, the theoretical advantage of longitudinal flow through a shallow depth to provide hydraulically optimum conditions for sedimentation was not forgotten. The idea was applied to small diameter tubes in order to meet the requirements of shallow depth at reasonable overflow rates. Initial studies indicated that settled sludge could be readily removed by periodically draining the tubes. An inclination of 5^{o} in the direction of flow was found to be adequate for sludge removal by gravity. At an inclination of 60^{o} the tubes are self-cleaning and do not even require periodic draining (15). The application of tubes overcomes the former sludge removal problems of trays and still benefits from the application of shallow depth sedimentation.

An application of tray sedimentation with a means of effective sludge removal will be even more advantageous than tube settlers. A fairly deep basin is required for tube settlers into which the tube modules must be installed. The tube modules provide the required solids removal capability of the basin. Tray clarifiers could be constructed without the need of deep basins, possibly saving on some of the capital investment necessary. Effective sludge removal is provided by controlling the flow through the clarifier in a manner that during predetermined times, a portion of the clarifier is being washed of the collected solids. The solids are washed to a mixing tank and later returned to the aeration tank as required in the extended aeration process. The flow in each channelled portion of the clarifier is controlled by a horizontal flow control syphon. Small effluent syphons provide for effluent draw-off from each section of the clarifier.

5. CONCEPT OF SYPHONS

The use of syphons to control flow in horizontal channels is quite unique. The concept of syphoning fluid from one level to another due to differences in elevation, in this application, is actually slightly exaggerated. A difference in elevation does exist through the syphon and the flow is stopped when air is introduced. Although, the conditions of flow more closely resemble flow in a conduit to a lower point rather than a syphon. The syphon action begins when the flow has been stopped in a particular channel and is then restarted. The syphoning causes the fluid to be drawn through the conduit, from the upper level near the trays to the mixing tank.

The effluent draw-off is a more true use of a syphon. The effluent is drawn from a lower level upwards, due to the weight of the fluid, into a trough for discharge.

6. DESCRIPTION OF BRANDON'S CLARIFIER AND SYPHON CONTROLS

The clarifier, at the city of Brandon, is curved, being constructed along the side of a circular aeration tank (17,18). The inlet and trayed section are 6'5" deep, 32' wide and 124' long. The syphon controls, following the trayed section, are 28' along the horizontal distance and as wide as the channels. The flow from the horizontal syphons is into a mixing tank which is 12' wide by 45' long with one end being 6'6" deep and the other 19' deep.

The clarifier inlet is a slot, 18" deep by 26'9" long, followed by a sloping ramp which opens to an area 8' wide across the front of the channelled section.

The channelled area, where sedimentation occurs, consists of eight 3'6" wide, 6'5" deep and 116' long channels. Each channel has three trays providing four 14" settling levels. The total clarifier operating depth is 5'.

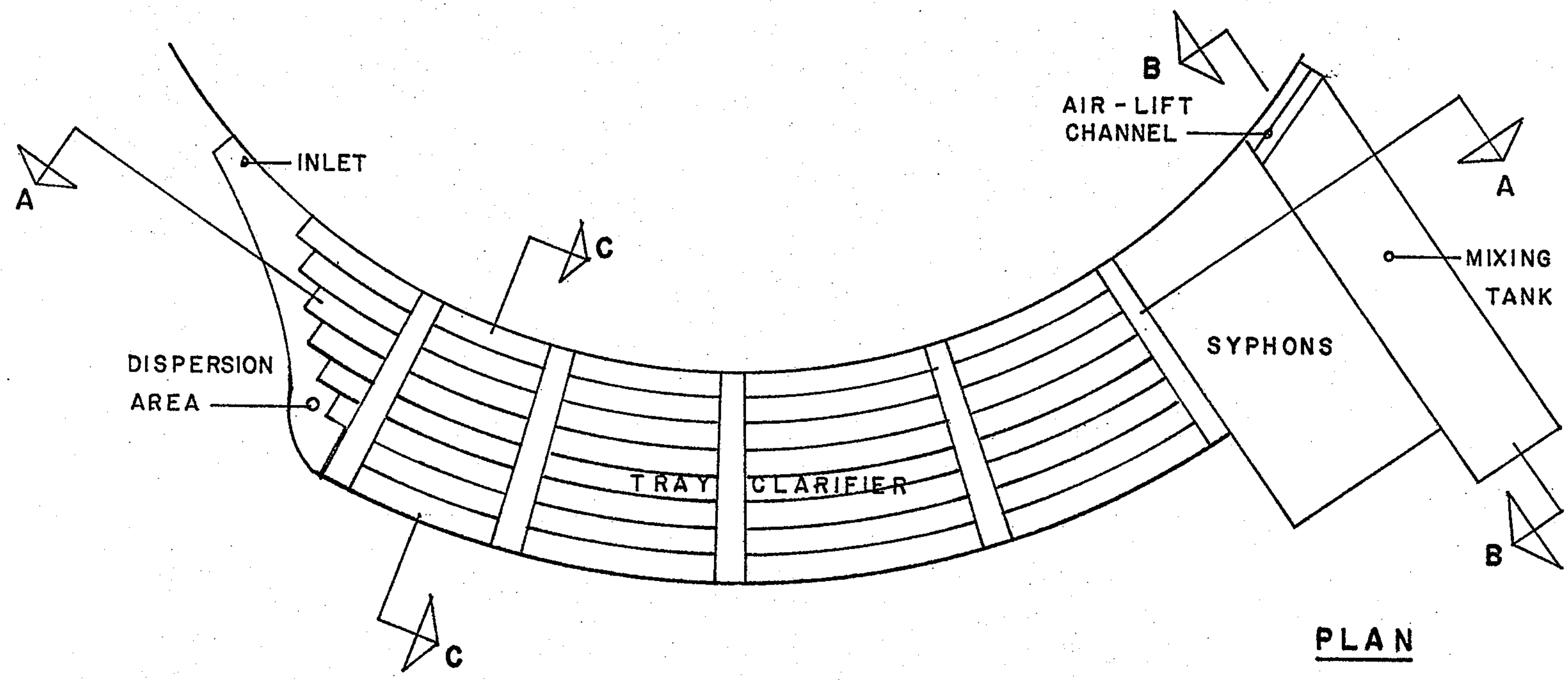


Figure 12: Plan view of clarifier.

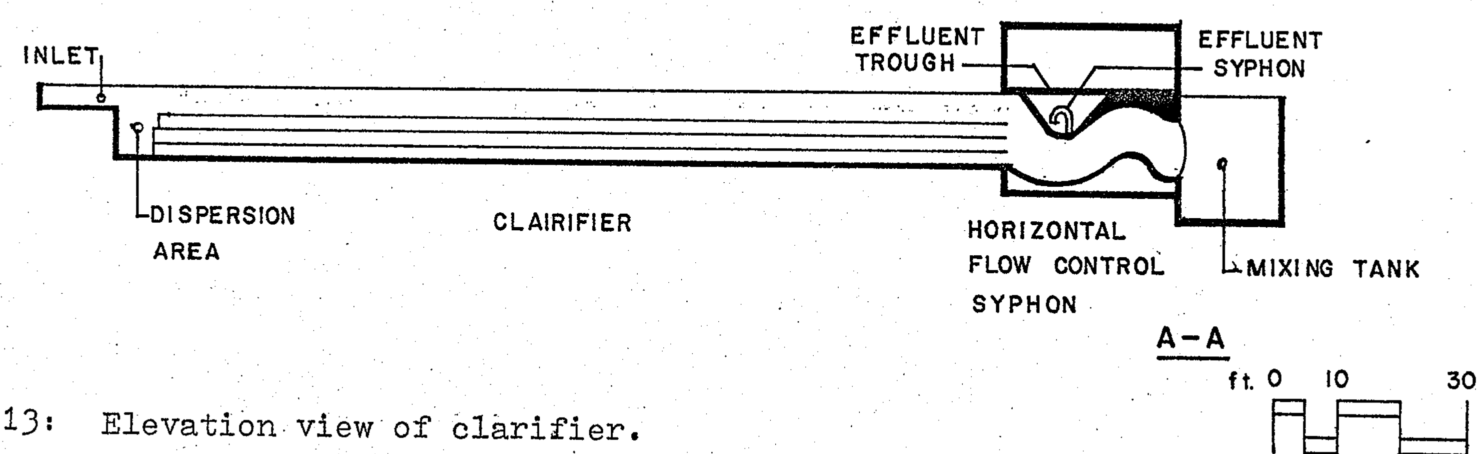
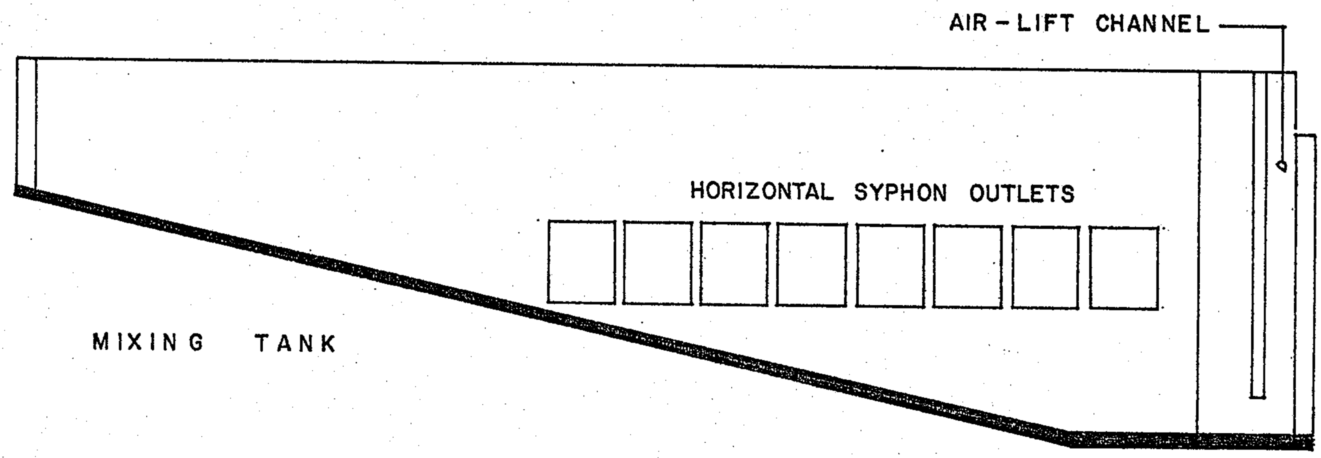
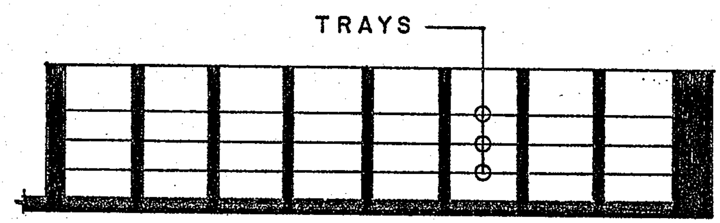


Figure 13: Elevation view of clarifier.



B – B

Figure 14: End view of syphon outlets and mixing tank.



C – C

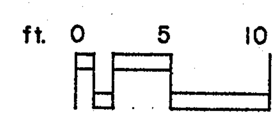


Figure 15: End view of channels with trayed levels.

The syphon controls are horizontal syphons 4'3" deep and 3'6" wide with an upper arched portion enabling the introduction of an air lock for flow stoppage and smaller syphons controlling effluent draw-off, located just prior to the arch for flow control. The effluent syphon pipe is 12" in diameter, with an orifice plate on the discharge side. Effluent is syphoned into an effluent trough above the horizontal syphon. The flow through both syphons is controlled by air locks, with the discharge from the effluent trough being further regulated by a weir.

In the mixing tank, following the syphon controls, is an air-lift channel with circulation pumps which return solids mixed with raw sewage to the aeration tank. The 1' wide air-lift channel with adjustable walls is on the deeper end of the tank beside the aeration tank. An 18" opening is provided along the bottom length of the air-lift channel to act as an inlet for solids and sewage which are displaced into the aeration tank. The air for the air-lift is supplied through two perforated 3" diameter pipes across the length of the channel.

6.1. Operation of the Clarifier

The operation of the clarifier at Brandon is relatively simple and may best be described and understood by discussing one channel and then describing how all eight channels are used simultaneously.

The operation begins with the channel having the mixed liquor flowing through, at a velocity which does not permit settling. The horizontal flow is stopped by the introduction of an air lock in the arched section of the large horizontal syphon. All flow in the channel is stopped for a 20 minute settling period.

After the settling period, the small effluent syphon is opened, creating a channel velocity of 0.1 ft./sec. and effluent is withdrawn for a $3\frac{1}{2}$ hour effluent draw-off period.

At the end of the effluent draw-off period, the small effluent syphon is closed, by the introduction of an air lock, and the large syphon air lock is released. The release of the large flow-control syphon is done simultaneously with the start-up of the air-lift channel in the mixing tank. These simultaneous actions cause the flow to be re-established through the channel with a velocity sufficient to scour the settled solids from the trayed levels and channel entrance area. Channel flushing is maintained for a 10 minute period followed by another 20 minute settling period.

The operation of one channel requires the stoppage of flow of settled sewage for one-half hour out of four. In order to accept the continuous flow of raw sewage, the treatment plant must be able to discharge treated sewage on the same basis. To maintain a continuous flow of effluent of sufficient capacity, the addition of the other channels is required. The full operation of all eight channels is for a careful sequencing of flushing, settling and effluent draw-off maintaining a continuous flow of treated sewage.

7. DESIGN OF A TRAY CLARIFIER

7.1. General Features

7.1.1. Inlet

The slot inlet is designed to allow only the mixed liquor from the surface of the aeration tank to enter the clarifier. The inlet design must be adequate to allow for the ultimate flow demand, based on channel sequencing to be used.

The inlet ramp and distribution area are designed to distribute the flow to any channel, which requires the additional volume of mixed liquor for flushing. The distribution area is designed with a sufficient width to minimize and dissipate eddy currents, although not of such width as to permit collection of settling solids. The distribution area is designed to permit the development of sufficient flushing velocity to adequately flush the settled solids from the trayed channel and distribution area.

7.1.2. Channels

The channel entrance is designed to ensure that excessive currents are not developed during the operation of adjacent channels.

The channel width must be designed to prevent undesirable turbulence and velocity gradients from developing during operation.

The channel length and tray spacing are designed to consider the type of solids to be settled, the volume of solids to be settled and the settling velocities of the particles. The design must take into account the amount of flushing that will be required and the effectiveness of flushing, considering the length of channel.

7.1.3. Syphon Controls

7.1.3.1. Channel Flow Control

The horizontal flow control syphon is designed to provide a head differential from the syphon inlet to the outlet. The head differential must be adequate to enable the re-start of channel flow, after releasing the channel air lock, yet not be too great to prevent the stoppage of flow by means of the air lock.

The curvature of the syphon is designed so that the shape does not create too great a head loss. The amount of head loss is significant in designing the size of the air-lift which is required to create adequate flushing velocity.

The horizontal flow control syphon is designed with an arched portion which is adequate to stop flow by the introduction of air to form a lock. The design elevations on both sides of the arched portion and in the center "hump" are important to insure the stoppage of horizontal flow yet should not hinder the re-establishment of flow. The outlet elevation must be designed to release any excess air pressure in a manner which will not disrupt settling. The area near the effluent draw-off point is designed to ensure that scour velocities do not develop during periods of effluent draw-off.

7.1.3.2. Effluent Flow Control

The effluent draw-off syphons are designed to ensure equal flow from each channel. The syphon includes an orifice plate designed to provide sufficient hydraulic loss to ensure a flow in the channel that does not affect settling. The hydraulic loss calculation must consider the effluent trough weir elevation for control of effluent draw-off and preventing any flow from excess pressure during channel flushing. The effluent syphon must completely stop flow.

7.1.4. Mixing Tank

The mixing tank is designed to provide an adequate area for the mixing of the incoming raw sewage and the returned solids from the clarifier. The design must include the size of an effective air-lift which is required to create an adequate head for flushing velocities. Provision must be made in the tank to ensure that solids are moved towards the air-lift channel. The level of the incoming raw sewage and returned solids in the mixing tank is kept at the same elevation as the aeration tank. This is done by having the wall of the mixing tank at the aeration tank side adjusted to be lower than the elevation of the mixed liquor.

7.1.5. Air-lift Channel

The air-lift channel is designed to effectively displace the returned solids and raw sewage into the aeration tank and to provide an additional head differential from the trayed channels to the air-lift. The head differential must be sufficient to overcome any frictional loss and to create an adequate flushing velocity. The head differential must not be so great that an excessively large horizontal flow air-lock is required in channels not flushing.

The perforated air line supplying the bubbles for the air-lift are non-clog due to short tubes that extend from each hole. The tubes are slightly larger than the air hole. A small continuous discharge of air is maintained through the holes at all times to further aid in preventing clogging.

7.1.6. Air Piping and Controls

The air supply piping for the effluent syphon air-locks are designed with a minimum number of flat and curved sections that might collect solids which will foul the operation. The outlets for the effluent syphon air-lock pressure release are designed to discharge the air away from any area where personal injury, from the pressurized air, may be suffered.

The air valve controls must be of the type which ensure shut-off for air flow without any leakage. The possibility of solids entering the valve and fouling their operation must be taken into account.

7.2. Detention Periods

7.2.1. Channel Detention Periods

The detention periods of a channel are based on the type of solids, the settling velocity, and the volume of solids that are to be collected. The detention period for a channel must be sufficiently long to allow the settling of solids prior to effluent removal. The settling and effluent draw-off periods must be timed to insure that an excessive amount of solids does not collect on the trays, requiring a larger air-lift to aid in flushing the channel.

7.2.2. Channel Scheduling

In instances where additional removal capacity, without excessively long channels is needed, or expansion of existing facilities is required, the scheduling of channels may be such that more than one channel can be operated in parallel. If the unit operation of two or more channels is to occur simultaneously, the design of the system must include provision for an adequate flushing velocity, and the velocity of flushing of adjacent channels does not interrupt the settling processes of nearby channels.

7.3. Hydraulic Factors

7.3.1. Inlet

The slot inlet is not designed to regulate incoming flow. The inlet must only be capable of allowing a sufficient volume of mixed liquor to enter from the surface of the aeration tank. Predicting the flow through the slot cannot be done accurately, since the flow is over a submerged weir and does not form upper and lower aerated nappes (7,19). The design must be approximated to provide the necessary capacity.

The inlet ramp and distribution area are designed to direct the flow and allow for its distribution to the trayed channels in a simple manner. The velocity of the incoming fluid varies inversely with the area, since $Q = A_1V_1 = A_2V_2$ where Q = discharge, A = area and V = velocity. Consideration must be given to friction losses from the side walls and channel bottom.

7.3.2. Channels

The design for channel velocity must be done considering two separate conditions, channel flushing and effluent draw-off. In each channel the trays alter the normal flow patterns expected for a rectangular channel. The flow patterns actually approach conditions of closed rectangular shaped full flowing conduits for the lower levels with the uppermost level being a shallow open channel. The alteration in flow patterns affects the conditions which must be considered to design for the desired channel velocity. The conditions of flow in a channel may be made more similar by making the resistance to flow of the different levels approximately equal. The depth of the uppermost level may be reduced, inducing a proportionately greater amount of drag per unit of flow and at a lower energy level. If the conditions of flow for the trayed levels are almost the same, the operation of the channels will be more satisfactory.

The velocity to be developed within a flushing channel has only one requirement, that it be great enough to scour the settled solids from the trays. The flow pattern which will be most critical is the flow in the lower levels, if the conditions of flow are not designed similar. The lower levels provide more resistance to flow than does the uppermost. Therefore, if the lower levels meet the necessary conditions for flushing, the upper level will also. The velocity of flow necessary in the closed conduits may be approximated using the Moody Resistance Diagram after correcting for the difference in the hydraulic radius of the rectangular conduit, by using $R = A/P = D/4$ for a circular pipe where R = hydraulic radius, ft.; A =

area, sq. ft.; P = wetted perimeter, ft.; D = diameter of pipe, ft., calculating the Reynold's number as Re = $\frac{4RV}{\nu}$ where Re = Reynold's number; V = velocity, ft. per sec.; and ν = Kinematic viscosity, sq. ft. per sec. The head loss equation becomes (7):

$$h_f = f \frac{L}{4R} \frac{V^2}{2g} \qquad \text{......... (17)}$$

where f = resistant coefficient
L = length of conduit, ft.
g = gravitational acceleration, ft. per sec.^{2}

The velocity during effluent draw-off periods must not resuspend settled solids. Solids that are re-suspended may be carried along the level and be syphoned out with the effluent. The maximum velocity that can be allowed during effluent draw-off must therefore be less than the scour velocity along any point in a channel. The velocity must also be low enough to allow for a sufficient settling period for the incoming mixed liquor. The flow pattern which will be most critical is the flow in the uppermost level. The velocity of flow may be approximated by Manning's Formula for open channel flow (7,19):

$$V = \frac{1.49}{n} R^{2/3} \; S^{1/2} \qquad \text{......... (18)}$$

where V = velocity, ft. per sec.
n = Manning roughness coefficient, ft.$^{1/6}$

R = hydraulic radius, ft.
S = slope of channel

7.3.3. Syphon Controls

7.3.3.1. Channel Flow Control

The head differential designed into the horizontal flow control syphon is provided to aid in overcoming frictional and energy losses encountered by the flow through the syphon during periods of channel flushing. The prediction of the hydraulic losses through the syphon can only be approximated. The nearest estimation for the losses may be calculated by assuming the flow to be through a rectangular conduit and adding a safety factor to the calculation.

7.3.3.2. Effluent Flow Control

The rate of flow through the effluent syphon is regulated by an orifice plate. The flow through the orifice may be calculated by utilizing Bernoulli's equation to develop (7):

$$Q = \frac{C_c \; C_v \; A_2}{\sqrt{1 - C_c^2 \left(\frac{D_2}{D_1}\right)^4}} \sqrt{2g \; \Delta h} \qquad \text{........ (19)}$$

where C_c = contraction coefficient
C_v = velocity coefficient
A_2 = area of the orifice, sq. ft.
D_1 = diameter of the pipe, ft.

D_2 = diameter of the orifice, ft.
Δh = change in piezometric head, ft.

The discharge equation may be expressed more simply as (7):

$$Q = C_d A_2 \sqrt{2g \Delta h} \qquad \text{......... (20)}$$

where C_d = discharge coefficient

The effluent trough weir elevation is designed to regulate the pressure head on the discharge side of the effluent draw-off syphon.

7.3.4. Air-lift Channel

The entrance to the air-lift channel does not control the rate of flow from the mixing tank. The bottom entrance is used to ensure that solids and sewage are taken from the bottom of the mixing tank and displaced into the aeration tank. The head differential, developed by the air-lift channel, is created inside the channel section causing solids and liquid to enter from the bottom and further be displaced into the aeration tank. The air-lift channel inlet should not restrict the volume of flow. The capacity may be approximated by assuming the situation to be flow under a sluice gate (7,19).

$$q = \frac{C_c \; C_v \; b}{\sqrt{1 - \left(C_c \frac{b}{y_1}\right)^2}} \sqrt{2g \; (y_1 - y_2)} \quad \ldots\ldots \; (21)$$

where b = height of gate from bottom, ft.
y_1 = height of fluid before the gate, ft.
y_2 = height of fluid after the gate, ft.

The flow created by the air-lift channel is regulated by the quantity of air supplied to the channel.

7.4. Safety Factors

Safety factors in the design, capable of adjusting for the many approximations that must be made for channel flow, losses in the horizontal flow syphon, and clarifier operating depth are incorporated into the design of the air-lift channel. The channel is designed with adjustable walls. One wall allows for the adjustment in the opening into the air-lift channel. The other wall allows for the elevation of the head differential created by the air-lift to be adjustable. The control of air being supplied to the air-lift and selecting the elevation of the wall, separating the air-lift from the aeration tank, make the head differential adjustable. The control of the head differential developed by the air-lift channel allows for further adjustments after construction to ensure proper operation.

8. CONCLUSIONS

Based on theoretical considerations from the theory sited in this work and observations of an actual operating clarifier, the following conclusions have been arrived at:

1) A clarifier with a shallow sedimentation depth, provided by trayed levels superimposed one above the other and with an effective means of removing settled solids, by controlling the horizontal flow provides a workable application of settling theory directly applicable to the extended aeration process.

2) A design incorporating a clarifier with trayed channels having the horizontal flow controlled by syphons offers conditions ideal for settling, reduced overflow rate for the effluent, reduced effects from outlet currents, and minimizes the effects of short-circuiting on the clarifier.

3) Providing proper consideration was given during the initial design, a clarifier with trayed channels may be more simply altered than a conventional design, for future expansion, by rescheduling the operation of the channels. A conventional design would require equipment additions or further construction.

4) A treatment plant utilizing a tray clarifier should be preceeded by flow equalization. The susceptability of the clarifier to fluctuations in flow, reducing the removal capability is quite high. The clarifier

operates best with a constant velocity and head.

5) A clarifier with trayed channels and the horizontal flow being controlled by syphons offers a treatment plant operator some control of the clarification process. The settling period may be lengthened or shortened as required and the rate of effluent draw-off may be altered by minor changes in the draw-off syphons.

6) The superimposing of trays one above the other reduces the total area necessary for a conventional clarifier. This may provide a savings in capital costs.

7) The hydraulic factors involved in the design of a tray clarifier are not very accurately predictable. Some educated guesses must still be made.

9. RECOMMENDATIONS

Additional study should be made on the hydraulic factors involved in the design of the trayed clarifiers to determine the effect of:

- the curvature of the horizontal flow control syphon tunnel on head loss during channel flushing

- varying the size of the submerged inlet and the air-flow rate on the operation of the air-lift channel

- the submerged wall at the slot inlet for the flow entering the clarifier

- the shape of the inlet ramp in dispersing the incoming mixed liquor along the dispersion area.

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11. VITA

a) Born Winnipeg, Manitoba, 28 January 1952.

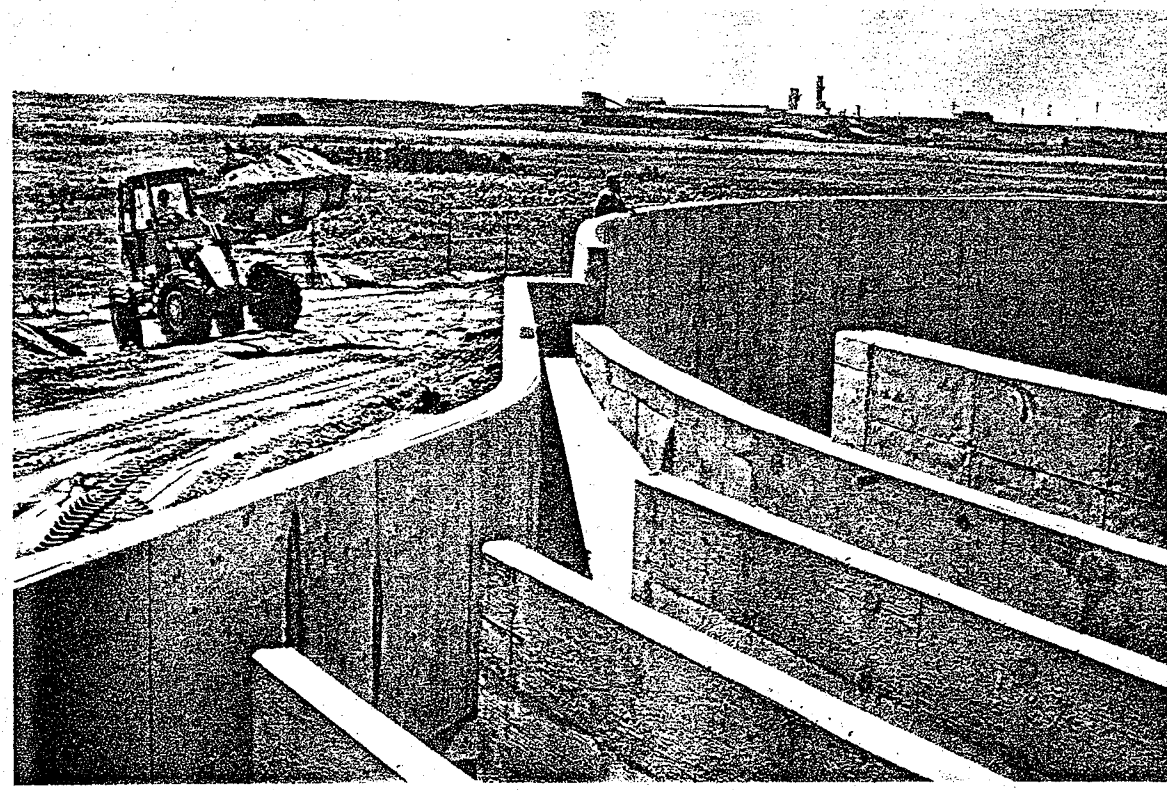
b) Graduated Kelvin High School, 1970.

c) Bachelor of Science (Civil Engineering), University of Manitoba, 1975. Undergraduate thesis "An Evaluation of the Operational Problems Associated with Extended Aeration Sewage Treatment Plants".

APPENDIX

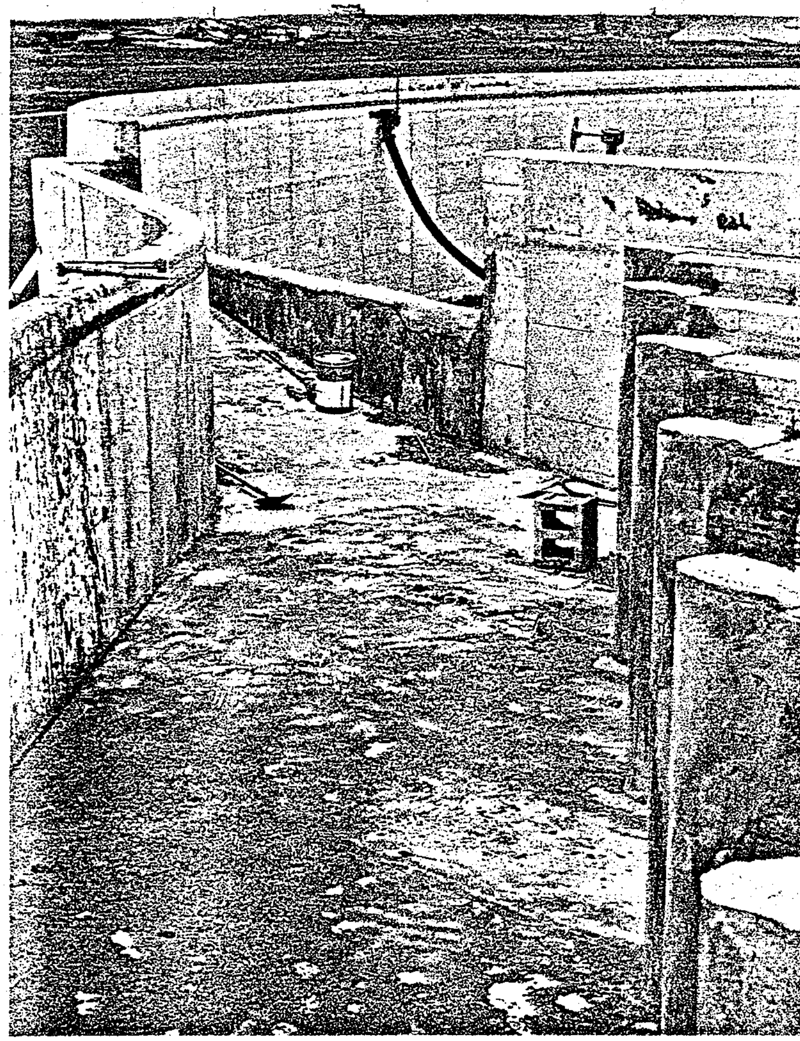
APPENDIX A

PHOTOGRAPHS OF THE CLARIFIER AT BRANDON, MANITOBA



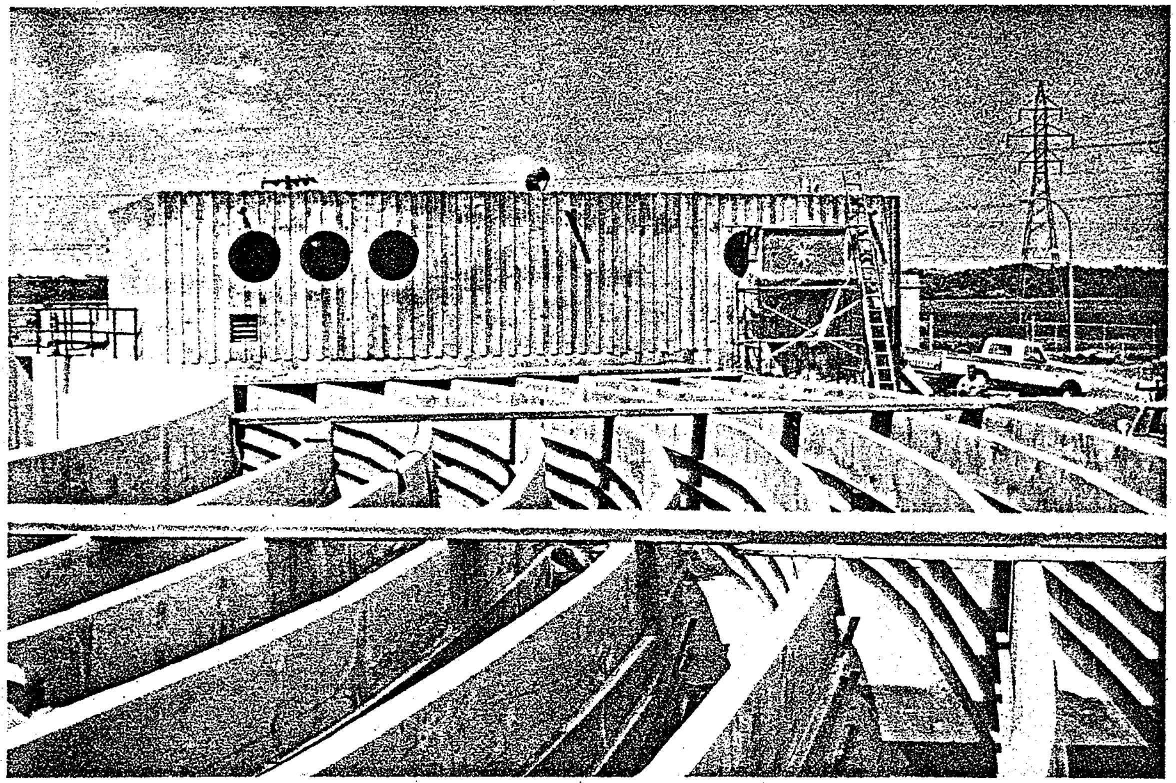
Photograph 1:

Slot inlet from aeration tank with entrance ramp and distribution area just prior to trayed channel area. (Modifications to channel entrance area at a later date provided for larger distribution area and curved wall sections for channel entrance.)



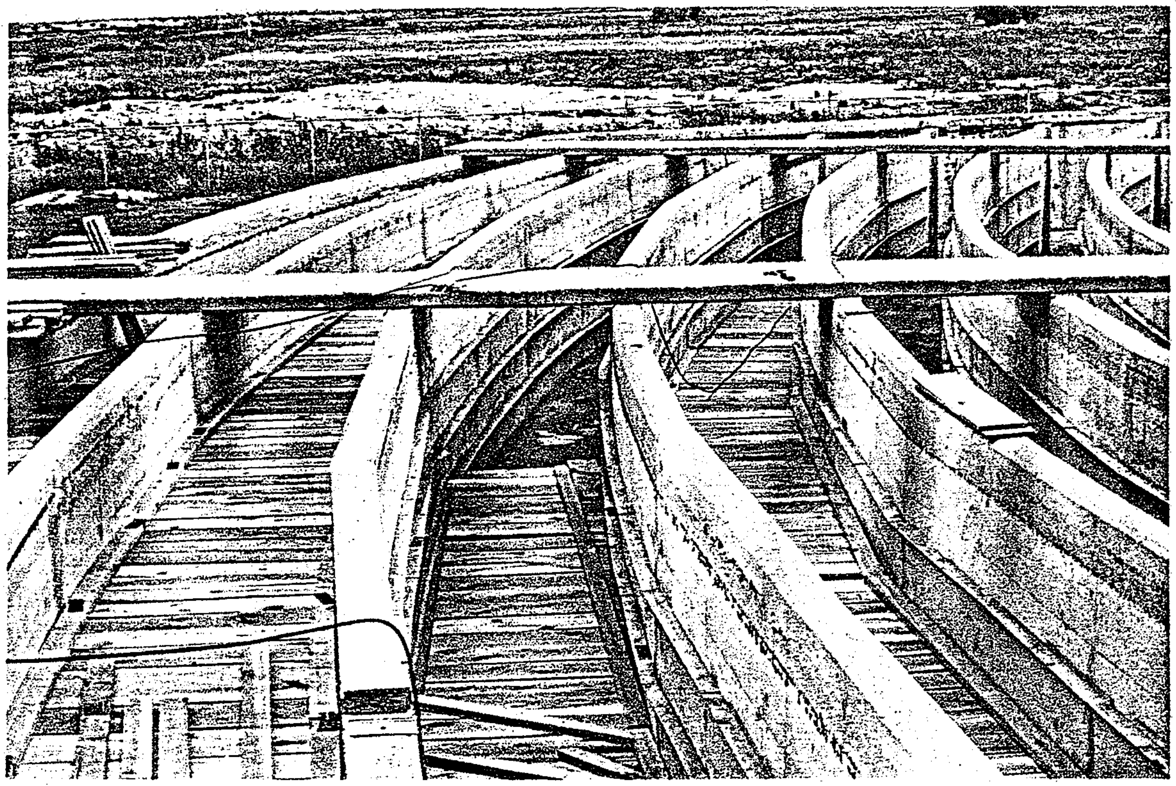
Photograph 2:

Distribution area prior to trayed channel area, slot inlet and entrance ramp with aeration tank in background. (Modifications completed.)



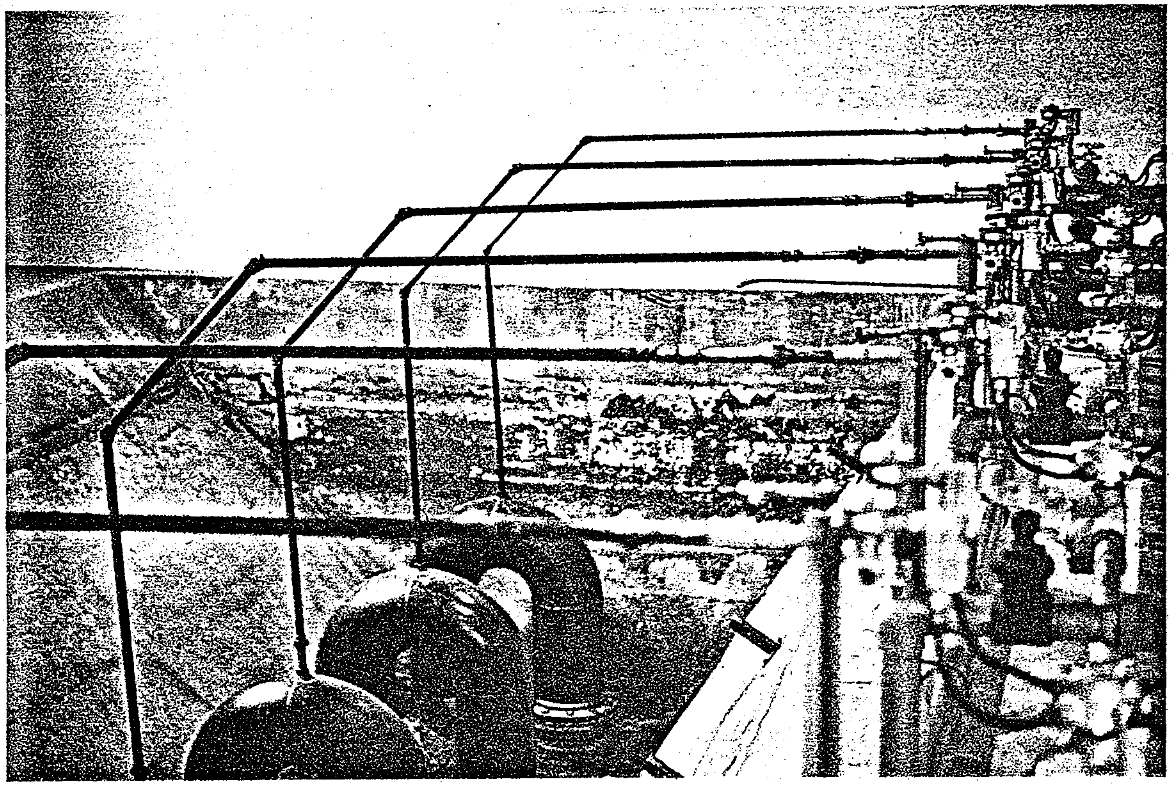
Photograph 3:

Trayed channel area, without trays, looking from the distribution area. Syphon controls and effluent collection trough are contained in structure in background. Note the brackets to support the three trays in each channel.



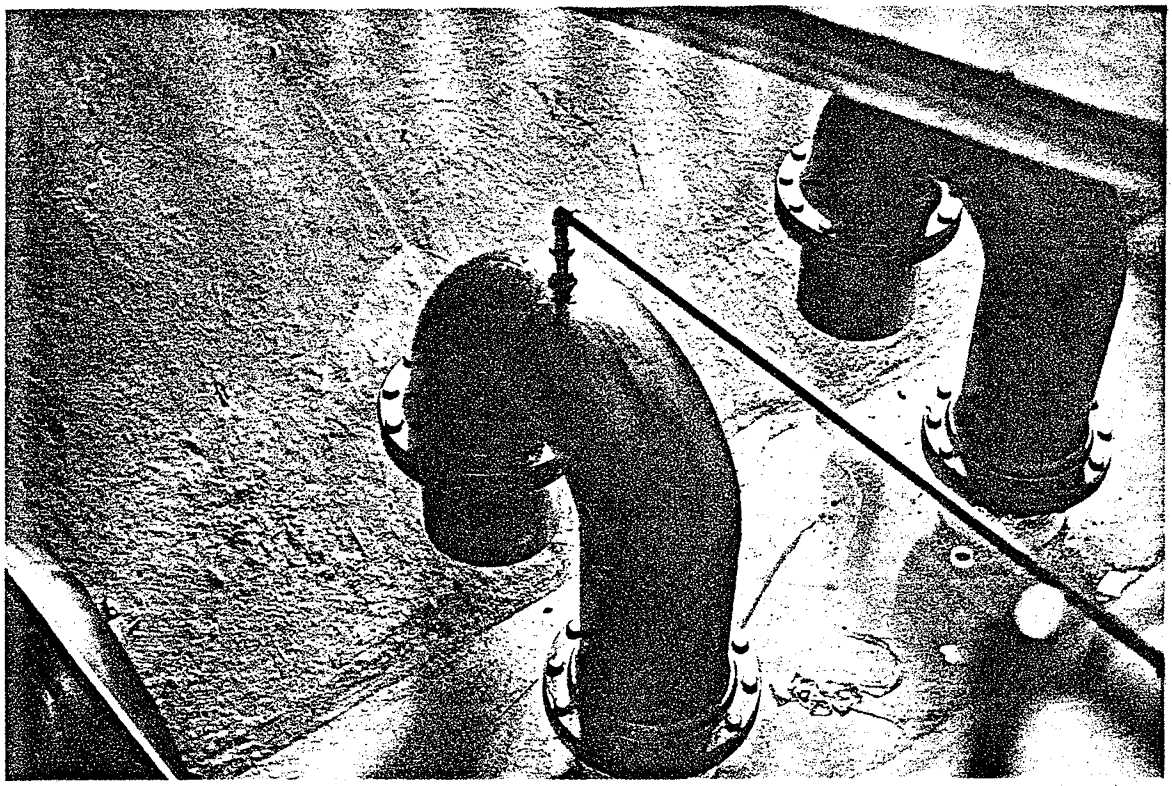
Photograph 4:

Trayed channel area, looking towards distribution area. The trays are being installed. Construction is of cedar planking, anchored on brackets along wall with two by fours.



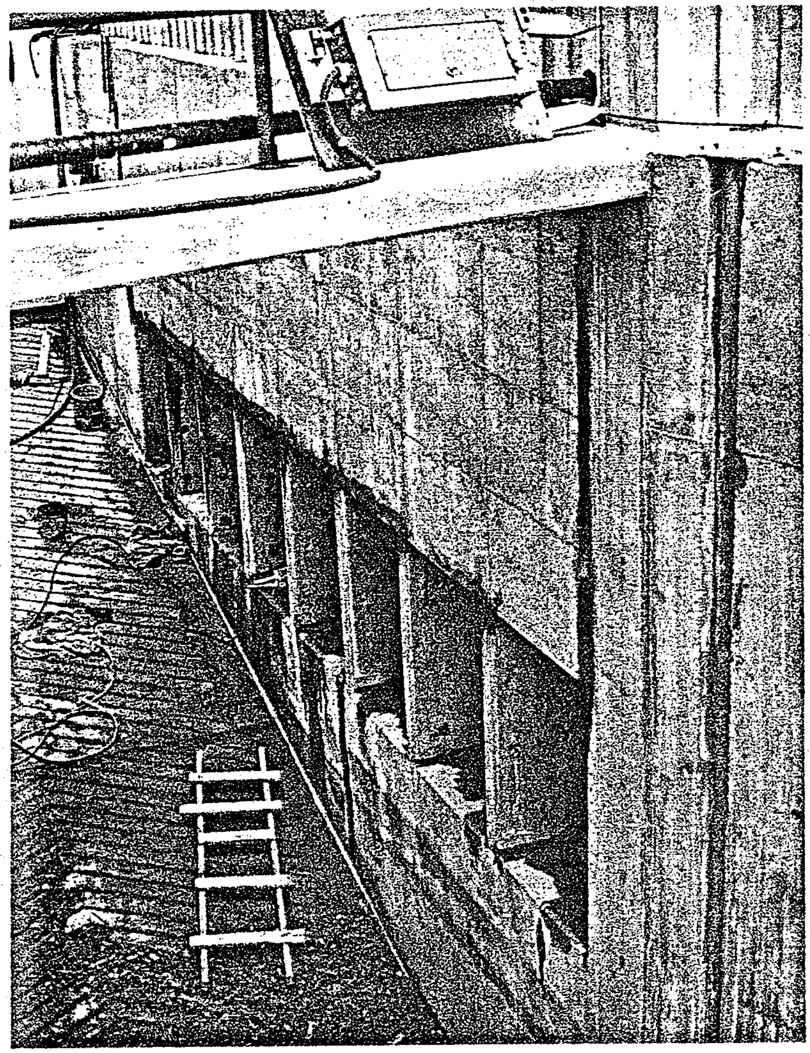
Photograph 5:

Effluent trough, contained in structure at end of trayed channel area. Some effluent draw-off syphons can be seen with air valve controls and piping.



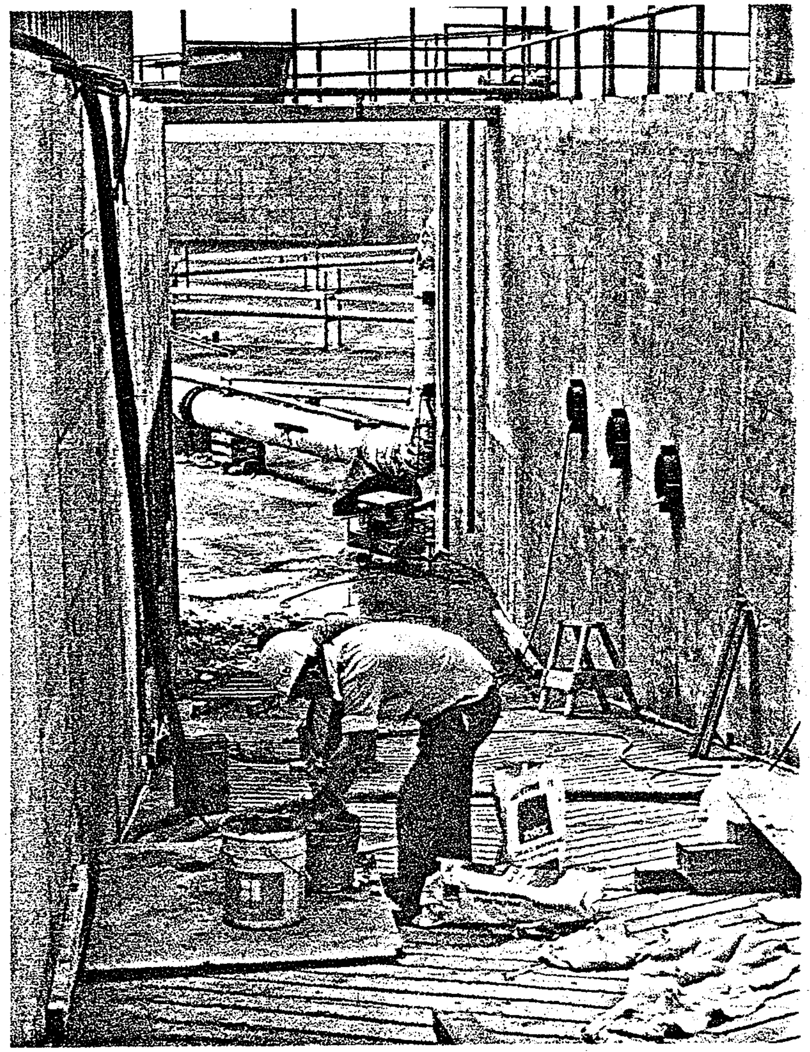
Photograph 6:

Effluent draw-off syphon, notice the oriface plate on discharge side of the pipe. Air-lock is maintained in the upper arch of the pipe. (Air supply pipe was modified at a later date to be a direct connection as shown in Photograph 5. This modification was done to prevent the collection of solids in pipe.)



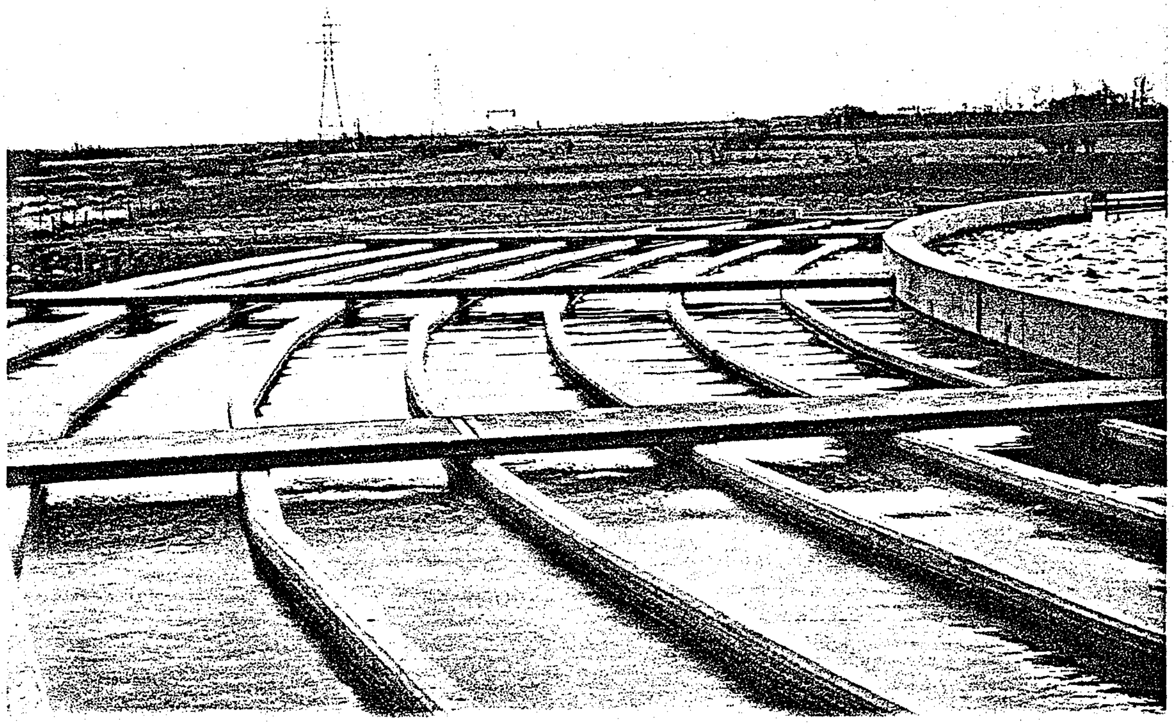
Photograph 7:

Outlets from horizontal flow control syphons into the mixing tank. Notice the slope for the bottom of the mixing tank, aiding in the movement of solids towards the air-lift channel. The air-lift channel will be located in the immediate foreground.



Photograph 8:

Mixing tank, following the horizontal flow control syphons. The bottom of the tank slopes downward to the air-lift channel, not yet in place. The guides for the wall pieces are in place at the end of the wall on the right. Notice the spacing for the inlet to the air-lift channel. Inlets to the circulation pumps are on the right, with the aeration tank in the background. Syphon outlets are on the left.



Photograph 9:

A view of the clarifier facing the inlet and distribution area. Notice the liquid level between the trays and aeration tank.

APPENDIX B

SUMMARY OF DATA

Summary of Data

The data presented is not representative of the clarifier's operation. The analyses were of mixed liquor, suspended solids and clarified effluent from the treatment plant operating during the winter months of 1974 - '75 and '75 - '76 without an aerobic floc having been developed. Design changes were made to the dispersion area and at the channel inlets for the winter of '75 - '76.

Date	Mixed Liquor Suspended Solids (mg/l)	Clarified Effluent Suspended Solids (mg/l)
November 14, 1974	185	710
21	1440	142
28	2270	170
December 6	N.D.*	300
13	1730	290
22	1880	460
January 3, 1975	2220	337
February 16	N.D.	167
19	2480	228
27	N.D.	225
March 7	2050	318
October 30	1850	194
January 14, 1976	2000	135
21	2038	N.D.

* N.D. - no data